

# A Study on the Operation Performance of a Minienvironment System

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## Abstract

*A minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment. Minienvironments have been gaining popularity as a means to provide effective containment for critical contamination control. The use of minienvironments can provide several orders of magnitude improvement in particle cleanliness levels, while energy intensity may be shifted from the conventional cleanroom systems to the minienvironments that enclose specific processes. Prior to this study, there was little information available or published to quantify the energy performance of minienvironment systems. This paper will present quantitative results from a recent study of the operation performance of an open-loop minienvironment air system in a ballroom setting, including quantification of operation range, energy performance index, pressure control, electric power density, and airflows. The paper also provides a comparison of the newly measured results from this study with previously measured cleanroom performance. The results can serve as a starting point for identifying areas for energy savings from applying high-performance minienvironments in cleanrooms.*

## KEY WORDS

Minienvironment, energy performance index, airflow, electric power, pressure control, cleanroom, separative devices

## INTRODUCTION

A minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment.<sup>1,2</sup> Minienvironments, often termed “separative devices,” have been gaining popularity as a way to provide effective isolation for critical contamination control. The purpose of using minienvironments is either to protect contamination-sensitive products or processes by isolating them from the ambient environment and workers, to protect workers or their environment from exposures to hazardous contaminants by isolating the products or processes, or both. Minienvironments can often introduce filtered air through high-efficiency particulate air (HEPA) or ultra-low-penetration air (ULPA) filters at a high airflow speed (e.g., 0.45 meter per second [m/sec] or 90 feet per minute [ft/min]) in order to achieve the desired pressure difference or unidirectional airflows to maintain specific levels of cleanliness and contamination control.<sup>3</sup>

Depending on the actual height of minienvironment spaces, air change rates of the supplied air can be much higher than the air change rates of recirculation air in common cleanrooms that are designed to achieve a similar cleanliness classification.

Based on anecdotal industry experience, in some situations a minienvironment (or isolated air space) simply creates additional air movement, air conditioning, and energy requirements, with little change to the design and operation of the overall cleanroom. While there are papers and guidelines addressing minienvironments’ design, construction, and operation<sup>4-11</sup> and yields and production associated with deploying minienvironments,<sup>12</sup> there is virtually no data available to quantify the energy efficiency of minienvironment systems.<sup>13,14</sup>

To understand actual energy implications of a minienvironment system, it is necessary to investigate energy performance of a typical minienvironment and understand its effect on overall cleanroom energy use.

## **OBJECTIVES**

The objectives of this paper are to:

- Develop an understanding of the key parameters contributing to energy performance of a minienvironment, including a list of key metrics to characterize the performance.
- Quantify energy performance of the minienvironment air system and identify opportunities for improving its energy performance.

This paper presents the measured energy performance of an air system of a selected minienvironment within the operating range of the minienvironment, and compares the energy performance of the minienvironment with that of cleanrooms previously studied.

## **METHODS**

The study is designed to measure airflow rates, electric power demand, and air pressures in the minienvironment under various operating conditions. The measured conditions cover the full range of operating points (airflow delivery) that the air system of the minienvironment can handle. The key parameters include electric power demand, airflow rate, airflow speed, air change rate, static pressure difference between the space inside the minienvironment and the space surrounding the minienvironment, and energy performance index (EPI).

### **Electric Power Measurement**

The power meter used in this study is a true root-mean-square (RMS) energy analyzer with an uncertainty of  $\pm 3\%$ . The power meter records electric current, voltage, power factor, and actual power supplied to the air delivery system for the minienvironment.

### **Airflow and Pressure Measurement**

A velocity measuring device attached to an electronic micro-manometer measures the average speeds of the airflow delivered out of the face of fan-filter units (FFUs) installed at the ceiling of the minienvironment. The size of individual FFU and HEPA filters is  $0.305\text{ m} \times 0.610\text{ m}$  ( $1\text{ ft} \times 2\text{ ft}$ ). The measurement uncertainty in airflow speeds is  $\pm 3\%$  of reading plus  $\pm 0.04\text{ m/sec}$  ( $\pm 7\text{ ft/min}$ ) from  $0.25$  to  $12.7\text{ m/sec}$  ( $50$ – $2500\text{ ft/min}$ ). Pressures are measured using a Pitot tube, with a measurement uncertainty of  $\pm 2\%$  of reading plus  $0.001\text{-in.-water column}$  ( $0.25\text{ Pa}$ ) from  $0.05$  to  $50.00\text{-in.-water column}$  ( $0.125$ – $12,500\text{ Pa}$ ).

## **RESULTS AND COMPARISONS**

The minienvironment in this study is a stand-alone open-loop system, with airflow coming through the FFUs from the surrounding cleanroom space (Figure 1). The supplied air is filtered through four FFUs, each  $0.305\text{ m} \times 0.610\text{ m}$  ( $1\text{ ft} \times 2\text{ ft}$ ) and  $0.610\text{ m}$  ( $2\text{ ft}$ ) deep. The floor size of the minienvironment is  $0.74\text{ m}^2$  ( $2\text{ ft} \times 4\text{ ft}$  [ $8\text{ ft}^2$ ]) with an inner space height of  $2.3\text{ m}$  ( $7\text{ ft } 6\text{ in.}$ ).



*Figure 1. Open loop minienvironment in a ballroom setting.*

The supply air is from the top of the minienvironment and the exhaust opening is in the front toward the bottom. Each of the four identical parallel FFUs is designed with a single-phase alternating current (AC) motor with adjustable airflow rates or air speeds controlled by a silicon controlled rectifier (SCR) controller. In this study, fan speeds are manually controlled by adjusting the SCR controller to record the full-range operating conditions produced by the minienvironment air system. The recorded data include the concurrent power consumption of the minienvironment air delivery system, airflow rate, and pressure difference for each operating condition.

In this study, the air change rate is defined as the airflow rates supplied to the minienvironment divided by the inner space volume of the minienvironment, i.e.,  $1.7 \text{ m}^3$  ( $7.5 \text{ ft height} \times 8 \text{ ft}^2 \text{ floor area [60 ft}^3\text{]}$ ). Numerically speaking, the air change rate expressed on a per hour basis ( $\text{m}^3\text{air/hr-m}^3\text{room}$ ) would equal the volumetric airflow rate expressed in cubic feet per minute ( $\text{ft}^3\text{/min}$ ). Therefore in this study, the magnitudes of airflow rate and air change rate are used interchangeably in the discussion about performance metrics as they relate to airflows.

### **Electric Power and Airflow Rates**

Reducing the operating airflow speed not only can reduce FFU fan power, but also may improve cleanliness, lower noise, and improve the operating life of the fan. Normally, one would expect fan power consumption to increase with an increase in airflow rates. Figure 2 shows that when the air change rate is lower than  $760 \text{ m}^3\text{air/hr-m}^3\text{room}$ , which corresponds with airflow speed of  $0.47 \text{ m/sec}$  ( $95 \text{ ft/min}$ ), total electric power supplied to the FFU increases with the increase in airflow rates. In addition, the rate of the electric power increase is reduced when airflow speed is below  $0.47 \text{ m/sec}$  or  $95 \text{ ft/min}$  ( $21.5 \text{ m}^3\text{/min}$  or  $760 \text{ ft}^3\text{/min}$ ), at which total electric power input reaches a peak. In contrast, when airflow speed is above  $0.47 \text{ m/sec}$  ( $95 \text{ ft/min}$ ), total electric power decreases with the increase in airflow rate. This indicates that it takes less fan power for the air system of the minienvironment to run at a higher airflow rate than it does at a lower airflow rate. The dynamic power of the airflow increases; therefore, the efficiency of the speed control and motor combination improves at higher airflows than  $0.47 \text{ m/sec}$  ( $95 \text{ ft/min}$ ).

The trends observed in the figure also confirm that with this speed controller, once the initial resistance is overcome, the air delivery becomes easier (and therefore, more efficient) for the system to move the same airflow rate through the air system.

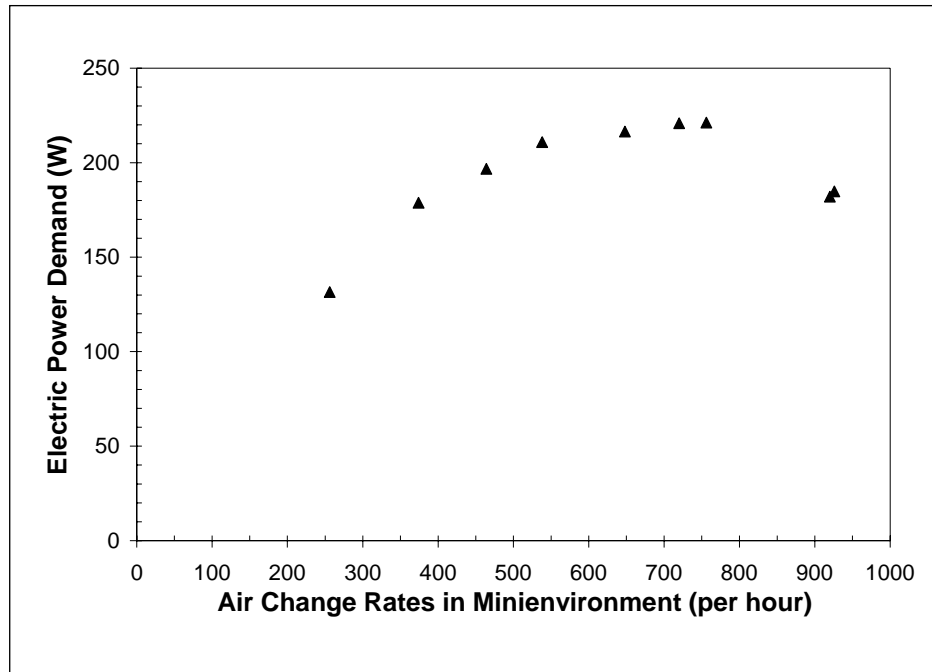


Figure 2. Electric power and airflow rates.

### Energy Performance Index

The energy performance index (EPI) of the air system of a minienvironment is defined as the total electric power supplied to the fan system divided by the flow rate of the delivered air to the minienvironment.<sup>13,14</sup> A higher EPI means more power is needed for the same airflow rates supplied to and through the minienvironment, corresponding to lower air delivery efficiency in the minienvironment.

Figure 3 shows the EPI of the air system ranging from 7.1 to 14.8 W/(m<sup>3</sup>/min) (0.20–0.42 W/(ft<sup>3</sup>/min)), corresponding to air change rates ranging from 460 to 920 per hour. The EPI range corresponds to airflow speeds from approximately 0.57 to 0.30 m/sec (115–60 ft/min), airflow rates ranging from approximately 13.0 to 26.1 m<sup>3</sup>/min (460–920 ft<sup>3</sup>/min), and positive air pressure inside the minienvironment in a range of 0.01–0.03-in.-water column (2.5–7.5 Pa). By controlling airflow, a positive pressure is created to prevent introduction of potential contaminants from the surrounding environment. For common airflow speeds of 0.25–0.45 m/sec (50–90 ft/min), measured EPI is within 10.6–15.9 W/(m<sup>3</sup>/min) (0.30–0.45 W/(ft<sup>3</sup>/min)).

For the entire operating range, the air system's energy performance index (W/(ft<sup>3</sup>/min)) is in the range of 7.1 to 18.0 W/(m<sup>3</sup>/min) (0.20–0.51 W/(ft<sup>3</sup>/min)) with airflow speeds ranging from 0.57 to 0.16 m/sec (115–32 ft/min). In general, EPI values decrease with the delivered airflow rates. In this minienvironment, EPI exhibits an almost linear correlation with airflow rates. The trend indicates that the air system EPI value becomes lower (more efficient in delivering the air) when the airflow rate through the minienvironment increases.

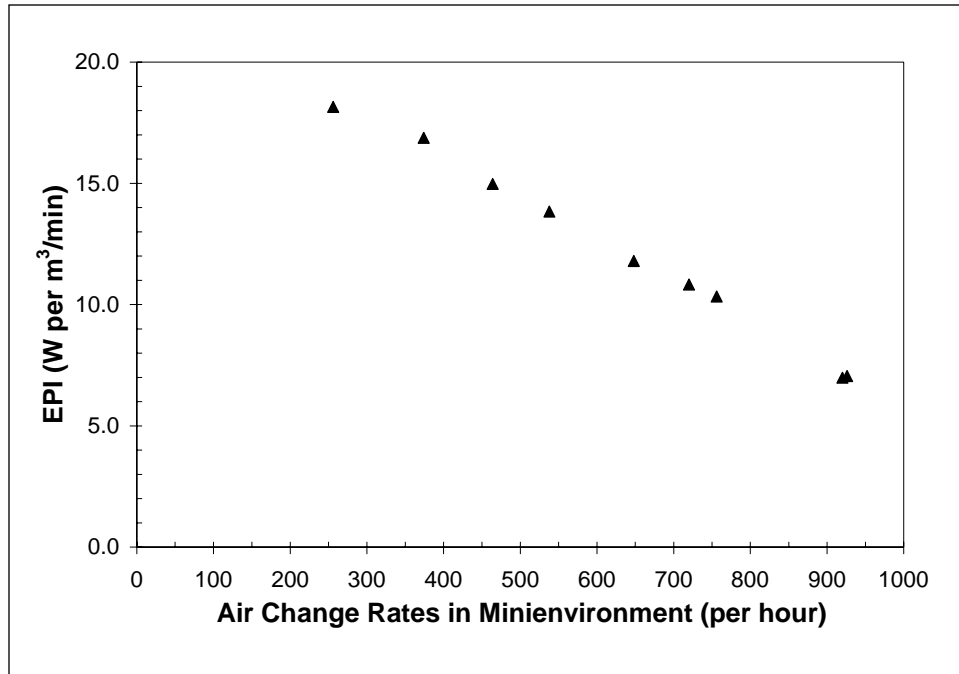


Figure 3. Energy performance index and airflow rate.

This entire operating range is within or lower than overall benchmarked ranges observed in many large cleanrooms (ISO Class 4 or 5). For example, EPI values of various ISO Class 4 cleanrooms in a previous study ranged between 7.4 and 18.7 W/(m³/min) (0.21–0.53 W/(ft³/min)).<sup>15</sup> Recirculation air system efficiency for ISO Class 4 and 5 cleanrooms collectively ranges from approximately 31 m³/min/kW to 297 m³/min/kW (1100–10,500 ft³/min/kW), corresponding to an approximate EPI range of 3.5–31.8 W/(m³/min) (0.10–0.90 W/(ft³/min)) for all recirculation air systems.<sup>15</sup>

Compared to FFU systems in ISO Class 5 cleanrooms, where EPI ranging from 26.5 to 27.5 W/(m³/min) (0.75–0.78 W/(ft³/min)) corresponds to average cleanroom air speeds from 0.10 to 0.15 m/sec (20–29 ft/min),<sup>16</sup> airflow speeds in the minienvironment are much higher and EPI values are lower. This indicates a more energy-efficient air system in the minienvironment than in the cleanrooms.

### Pressure Control

Air pressure differential is the difference between static pressure of air in the internal space of the minienvironment and that of the ambient surrounding of the minienvironment. The purpose of maintaining a positive air pressure in a minienvironment relative to air in the surrounding spaces is to prevent the less-clean air from being transported to the minienvironment and contaminating the process.

According to IEST-RP-CC028.1,<sup>1</sup> microelectronic minienvironments spanning between process bays and services chases should be designed to maintain a differential pressure, with a typical process bay pressure exceeding service chase pressure by 0.01–0.05-in.-water column (2.5–12.5 Pa). However, this range seems to be experiential, and there is no scientific data to specifically support such a range. A rule of thumb is to control pressure differential with a minimal value of 0.01-in.-water column (2.5 Pa) up to 0.03-in.-water column (7.5 Pa).

Figure 4 shows that, as expected, air pressure differential increased with delivered airflow rates, and that the increase rate of pressure differential is almost constant—indicating an almost linear correlation except for a few points, which are likely to be outliers in the measurement. A higher airflow tends to produce a higher air pressure differential. For example, with airflow speeds of 0.25–0.45 m/sec (50–90 ft/min), the pressure differential ranges from 0.008 to 0.02-in.-water column (2.0–5.0 Pa); with airflow speeds of 0.30–0.55 m/sec (60–110 ft/min), the pressure differential ranges from 0.01 to 0.03-in.-water column (2.5–7.5 Pa). The outliers of air pressure differential occur toward the higher end of airflow rates, and show a lower difference than if following the trend of the curve. This can be due to increased inaccuracies of static pressure sampling likely associated with increased turbulence at higher airflow speeds within the minienvironment.

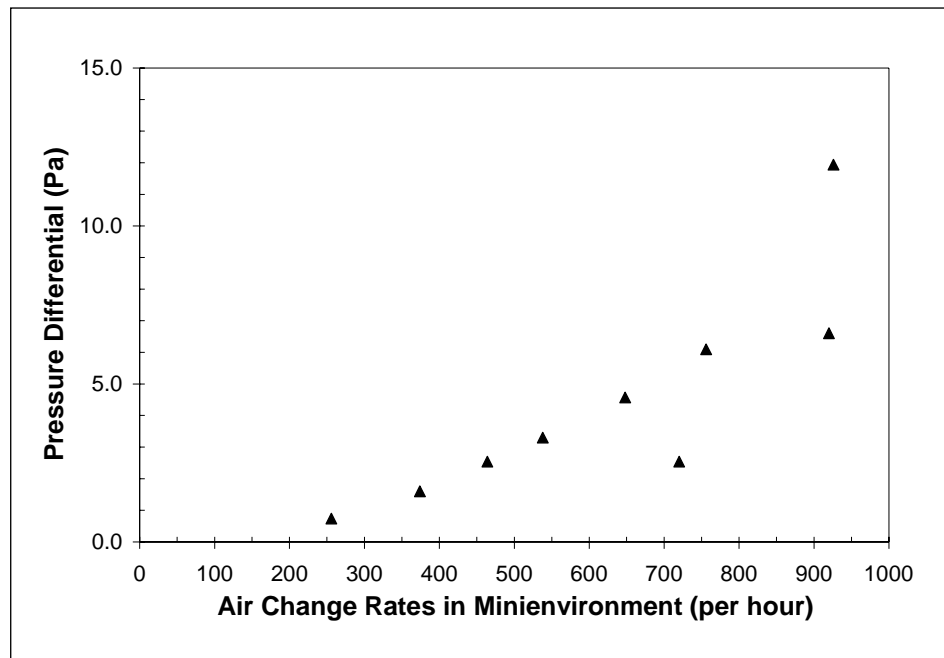


Figure 4. Pressure difference.

### Electric Power Density

Figure 5 shows that electric power density changes with average airflow speed inside the minienvironment. Corresponding to the tested operating ranges (0.16–0.58 m/sec or 32–115 ft/min) for this minienvironment, power density ranged from 177 to 249 W/m<sup>2</sup> (16.5–23.1 W/ft<sup>2</sup>), with a peak of 298 W/m<sup>2</sup> (27.7 W/ft<sup>2</sup>) when the air speed was 0.47 m/sec (95 ft/min). This range actually falls within the range of fan power density from previously measured ISO Class 4 cleanrooms with a range of 172 to 409 W/m<sup>2</sup> (16–38 W/ft<sup>2</sup>),<sup>15</sup> corresponding to 0.40–0.60 m/sec (80–120 ft/min). Given a same airflow speed in general, the FFU power density of the minienvironment tended to be slightly higher than those of cleanrooms of similar cleanliness requirements, especially when the cleanrooms are not fully covered by HEPA filters. Within a given time, the amount of airflow rate supplied to a minienvironment is

significantly reduced because of the much-smaller minienvironment volume compared to that of full-scale cleanrooms (e.g., ballrooms). This may suggest opportunities for significant overall energy savings if cleanroom airflows can be lowered due to vastly smaller volumes of air that must be moved, conditioned, and filtered.

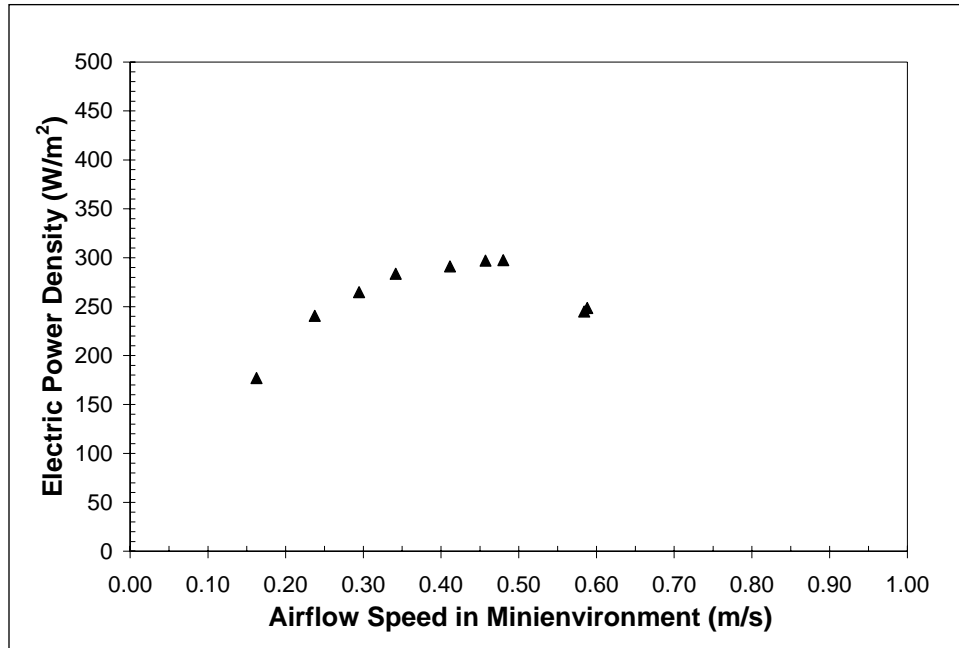


Figure 5. Power density and airflow speeds.

### Discussion of Airflows, Air Change Rates, and Cleanliness

In semiconductor wafer manufacturing, the air supply for a large ISO Class 4 or 5 ballroom is filtered and recirculated at rates as high as 500 or 600 air changes per hour ( $\text{m}^3\text{air/hr-m}^3\text{room}$ ), while wafer manufacturing takes place in a relatively smaller area within the whole cleanroom space.

In this case study, the minienvironment typically operates with once-through airflow speeds of 0.30–0.50 m/sec (60–100 ft/min), which is consistent with airflow speeds commonly observed in conventional large clean spaces. The HEPA/ULPA filter coverage in the minienvironment is 100% while cleanrooms can have coverage ranging from 20% to 100%. If airflows are converted into actual air change rates for the minienvironment studied, actual air change rates range from 480 to 800  $\text{m}^3\text{air/hr-m}^3\text{room}$ , corresponding to airflow speeds ranging from 0.30 to 0.50 m/sec (60–100 ft/min). The air change rate range is higher than the range observed in ISO Class 4 cleanrooms, which was in the range of 385–680  $\text{m}^3\text{air/hr-m}^3\text{room}$  corresponding to airflow speeds ranging from approximately 0.30 to 0.60 m/sec (60–120 ft/min).<sup>15</sup>

Particle concentration is not measured for the minienvironment in this study. Normally, a minienvironment in operation would be expected to produce no higher particle concentration than the thresholds established for cleanrooms with a certain ISO Class rating. For example, an ISO Class 4 minienvironment would contain no more than 10,000 particles equal to and larger than  $0.1 \mu\text{m}^3$  or 352 particles equal to and larger than  $0.5 \mu\text{m}^3$  of the minienvironment space.<sup>3</sup>

## CONCLUSIONS AND RECOMMENDATIONS

Minienvironment applications can largely influence future planning, design, construction, and operation of cleanroom spaces, depending on the specific contamination control requirements for the clean spaces. Contamination control for minienvironments can be realized by regulating airflow rates and air pressure differentials between the minienvironment and its surrounding space.

This study develops a new performance metric—energy performance index based on electric power usage per airflow rate—as a way to characterize the energy efficiency of airflow systems applicable to minienvironments. A lower energy performance index corresponds to a more energy-efficient air delivery system. Providing measured data to quantify energy performance of the minienvironment, this study shows that the energy performance index of a minienvironment for typical operation tends to be in the vicinity of or higher than that of its counterparts in traditional cleanrooms at a similar airflow speed. By the same token, electric power density of the air system in such a minienvironment can be higher than that of normal cleanroom systems.

This study suggests that the energy performance of devices, such as FFUs and their control mechanism, used in air systems largely affects overall energy efficiency of the air delivery system. Based on the analysis, implementing and integrating minienvironments as a means of contamination control may produce overall savings in electric power. Additional recommendations from this study include further understanding and investigation of the environmental and energy performance of minienvironments as compared to that of traditional cleanroom systems; developing methods of integration and optimization of minienvironments in cleanrooms; and further analysis of savings potential for future design, construction, operation, and management of cleanroom spaces.

## ACKNOWLEDGEMENT

This paper is based on the technical paper titled “Investigating the Performance of a Minienvironment System,”<sup>14</sup> produced from a research project funded by the California Energy Commission’s Public Interest Energy Research (PIER) Industrial program (<http://www.energy.ca.gov/>). This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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## **BIOGRAPHY**

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